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Utilization of pico hydro generation in domestic and commercial loads

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ABSTRACT

Pico hydro is a term used to distinguish very small-scale hydropower with a maximum electrical output of five kilowatts (5 kW). It is a good technique of providing electricity to the off-grid remote and isolated regions that suffer energy deficit. Typical pico hydro generator is designed and supported by electrical converting system, batteries and safety equipment so that it can be installed at the residential water pipeline. In pico hydro generation, the environmental impact is negligible since large dams are not involved, and the schemes can be managed and maintained by the consumer. This paper is reviewing the application of hydro generation and particularly focusing on the implementation of pico hydro generation system in University Malaysia Pahang (UMP) Campus-Pekan. This system was designed and simulated using the Matalb simulink blocks. The pico hydro generator has been tested in a real application with a pelton turbine design which utilizes a high pressure of water flowing from the main tank into the faculties. The speed of the turbine and alternator depend on the pressure of the water. In this work, a 1.05 kW alternator is used to charge the battery and the DC power output from a battery is converted into 220 V, 50 Hz.

Contents

1. Introduction

Hydropower plants is a clean source of energy that convert potential energy or water into electricity, the water after generating electrical power is available for irrigation and other purposes. The first use of moving water to produce electricity was a waterwheel on the Fox River in Wisconsin in 1882 [1]. Hydropower is the most widely used renewable energy source worldwide as it contributes 19% of the world's electricity power from both large and small power plants [2,3]. The water turbine was developed in the nineteenth century and was widely used for industrial power prior to electrical grids. Today, water turbines are mostly used for hydroelectric power generation [4]. In Malaysia, hydropower utilization for electricity generation started in July 1900 when a small hydroelectric plant was constructed on the bank of Sempam River near Raub, Pahang by the Raub-Australian gold mining company [5,6]. The utilization of hydropower in Malaysia to supply electricity for domestic use, however, was only commercially available around 1970s [5]. Although Malaysia had successfully benefited from large and small scale hydropower to generate electricity but no effort had been made to utilize hydro generation in the range of micro or pico hydropower systems [7]. If this potential is fully utilized, the power can be generated from a clean energy and this will provide a good solution for the problems of energy supply in remote and hilly areas where the extension of grid system is comparatively uneconomical.

Small hydropower systems are the application of hydroelectric power on a commercial scale supplying small loads and are classified by power and size of waterfall. This system can be divided into mini, micro and pico hydropower and recognized as key

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technologies in bringing renewable electricity to rural populations [8,9]. In the developing countries where funding is of primary concern, the micro and pico hydropower had already proven to be a practical and potential low cost option for generating electricity at remote sites, particularly for small villages in hilly areas. Micro hydropower sometimes includes pico hydropower and because pico hydropower generates electricity at household level, the distinction avoids confusion with larger micro hydropower systems which often operate at village level [10]. Some authors call very small (<5 kW) units "Pica-hydro", other authors put the upper limit of pica hydro as 20 kW [11]. During the last years, innovations in micro hydro technology have focused on the development of low cost implementation of stand alone pico hydropower to improve the affordability for low income households [12]. Up to now, self-excited induction generator and permanent magnet synchronous generators are presented as best variants for this type of generators [13,14].

Nowadays, new business opportunities have arisen in the field of establishing and operating small hydropower stations to generate electricity from environmentally friendly source (Run-of-river hydroelectricity) [15]. This type of hydroelectricity is the most expanded renewable energy source over the world and the main prospect for future hydro developments in Europe [16,17]. A micro hydro system has a quite large potential of development due to the increasing interest in renewable energies. In some countries such as India, China, Brazil and Kenya, the micro hydro projects are in the most cases implement standardized technologies for off grid decentralized village hydro schemes [15,18–21]. In other Asian countries, the micro hydro systems replaced the diesel generators and are used as hybrid systems with solar and wind powers [22,23]. In addition, the hydro energy have been used to produce a direct energy for small industries and agriculture such as battery charging, welding workshop, crop processing and grain milling in developing countries [24]. Since the hydro systems can be used as a direct mechanical drive scheme or electricity generation scheme, the installation of these systems in the remote villages and mountain areas will bring a huge social-economic development for these areas. Furthermore, it is possible for off-grid connection to serve as decentralized generation from hydropower to the surrounding areas if proven economical. Small hydropower projects are generally considered to be more environmentally favorable than both large hydro and fossil fuel powered plants [25]. Therefore, micro and pico hydropower systems can be said as principle renewable sources for sustainable development especially in developing countries.

2. Hydro generation classification

The large hydro generation comes from the potential energy of dam and connected to the National grid. Hydropower on a small scale is the most cost effective energy for rural electrification. The small scales of hydro generation are installed independently or connected to the micro grid. Pico hydro is the smallest stand alone power generation and mostly installed to supply very small loads. Different agencies use different upper and lower limits to classify the hydro generation depending on the generator capacity. However, an alternative definition of hydropower ranges is given in Table 1 [11,26,27]. The design of hydro generators is largely influenced by the relatively high runaway speed in which the machines may be subjected to turbine governor failure, and the high inertia usually incorporated into the machine rotor for system stability reasons or to provide satisfactory governing. Coupled with this, the turbine speed is relatively low, resulting in machines of very large physical size. For small hydro generators, adaptation of the designs from the manufacturers existing ranges of industrial machines is the usual approach but, irrespective of the machine size and its application, simplicity of construction with maximum reliability is the aim [28].

Table 1
Classification of hydropower generation.

Hydro generator	Capacity	Feeding
Large	More than 100 MW	National power grid
Small	Up to 25 MW	National power grid
Mini	Below 1 MW	Micro power grid
Micro	Between 6 and 100 kW	Small community or remote industrial areas
Pico	Up to 5 kW	Domestic and small commercial loads

The main design activity is mechanical in dealing with the rotor stress resulting from centrifugal forces at peripheral speeds. In this light, the choice of speed for the water turbine depends on the available head and the unit output required. The unit output may be limited by such factors as size of turbine runner, water flow and other factor related to the turbine and machine constructions. Currently, the small hydro generator design is based on permanent magnet technology. The generator itself has two electromagnetic components, the rotating magnetic field constructed using permanent magnets and the stationary armature constructed using electrical windings located in a slotted iron core. The voltage output from the generator is unregulated, multiple phase AC and varies as a function of the speed and load. This voltage output is connected to a solid state power conditioning system [25]. Due to the fixed excitation of the permanent magnet generator, it becomes very difficult to keep the operating speed constant at all load points. Therefore, the turbine is operated at constant gross head at all load points and other parameters are measured [29]. Typically, the solid state power conditioning system uses buck/boost techniques and regulates the entire power output.

High-speed mini, micro and pico turbines play a significant role in the distributed power systems that provide dependable electric power close to the user. In typical induction generator based small hydro schemes, the turbines used are run of the river type, where the water input and thus the mechanical power into the generator cannot be controlled. The same basic types of turbines are used as for high rating units, that is impulse (Pelton) and reaction (Francis, Propeller, Kaplan). The gross head available for power generation is usually recorded as the difference in elevation between the mean free water level of the delivery reservoir and the centre line of water admission into the turbine. Net head can either be calculated by deducting the pipe and fitting friction losses, or may be available from pressure gauge measurements [25,30,31]. Impulse turbines operate with ventilated tailraces, converting the kinetic energy of the free jets into mechanical energy of rotation. A particular machine may be applied over a small range in head and flow with acceptable variation of speed and efficiency. Reaction turbines offer better peak efficiency than impulse machines and are suited to applications where the site demand for water is unlikely to vary, but above or below design flow there is a loss of efficiency [28,32].

A turbine converts the energy from falling water into rotating shaft power based on a range of technologies that have been developed for lower and higher head pressures of various locations. Generally, reaction machines develop torque by reacting to the weight and low pressure of water whereas impulse machines develop torque from high pressure high velocity jets and therefore require casings. In other words, impulse turbines are used for high head sites and reaction turbines are used for low head sites. Accordingly, different types of turbine are used at different heads in order to maintain a shaft speed as close as possible to 1500 rpm for minimizing the speed change between the turbine and the

Table 2
Turbine type and head classification.

Turbine	Runner type	Head pressure	Height
Reaction	Propeller, Kaplan	Ultra Low	Below 3 m
Reaction	Propeller, Kaplan	Low	Above
Impulse	Crossflow		3 m
Reaction	Francis, Pump as Turbine	Medium	Above 40 m
Impulse	Crossflow, Turgo, Multi-jet Pelton		
Impulse	Pilton, Turgo, Multi-jet Pelton	High	Above 100 m

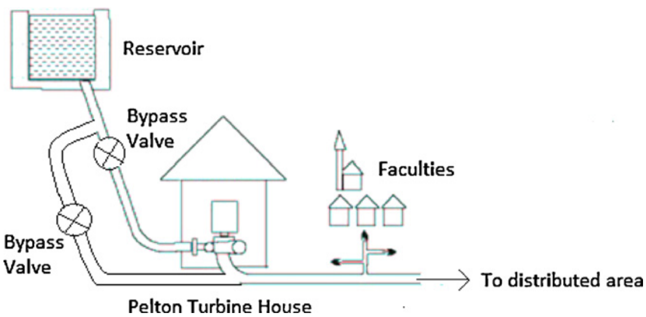


Fig. 1. Schematic diagram of the pico hydro generation in UMP.

generator. Due to this condition, the choice of turbine depends mainly on the head and desired running speed of the generator for locally manufactured pelton turbines [33]. Here, the adjustment of stream flow variations, water flow to these turbines is easily controlled by changing nozzle sizes or using adjustable nozzles. A classification of head pressure considering different turbine runner types is illustrated in Table 2 [11,26,33,34].

3. Pico hydro generation system in UMP

The water is supplied to UMP by conveying the water from a headwater reservoir via a pressure pipe as seen in Fig. 1. Normally, in this type of installation, the dissipation of energy at the lower end of the pipe at the entrance to the water treatment plant is achieved through the use of special valves. The fitting of a turbine at the end of the pipe to convert this otherwise lost energy to electricity, an attractive option provided that the water hammer phenomenon is avoided. Water hammer overpressures are especially critical when the turbine is fitted on an old pressure pipe [30]. To ensure the water supply at all times, a system of bypass valves should be installed. In some water supply systems, the turbine discharges to an open-air pond and the control system maintain the level of the pond.

The objective of a hydropower scheme is to convert the potential energy of a mass of water flowing in a stream with a certain fall to the turbine into electric energy at the lower end of the scheme where the pelton turbine house is located. The power output from the scheme is proportional to the flow and head. Since the proposed pico-hydro generator uses consuming water supplied by UMP tank, the practical method for head measurement is water-filled tube and calibrated pressure gauge. Through this method, the pressure gauge reading in psi can be converted to head in meters by [34],

$$h = 0.704 \times p \quad (1)$$

where h is the head (m) and p is the pressure (psi).

From Fig. 1, let us consider that the pressure of water is 0.01 bar, turbine efficiency 95%, water volume flow rate is 3 m^3/s and height is 1 m. The calculation of the maximum power gained from hydro turbine can be achieved by finding the pressure as [1,3,31],

$$p_{total} = p_{atmosphere} + p_{fluid} \quad (2)$$

where p_{fluid} is the net fluid pressure and can be defines as,

$$p_{fluid} = \rho \times g \times h \quad (3)$$

where ρ is the fluid density, g is the gravity acceleration and h is the head height.

The fluid power defines as,

$$P = p_{total} \times n \times Q \quad (4)$$

where n is the turbine efficiency and Q is the volumetric flow rate.

Thus, the maximum power that can be achieved is given as,

$$P = \rho \times g \times h \times n \times Q \quad (5)$$

As a result,
p_{total} = 0.01 bar
Conversion to SI unit: 1 bar = 100 kPa thus, 0.01 bar = 1 kPa.
Finally, the electric power is, $P = 1000 \times 0.95 \times 3 = 2850$ W.

4. Case study

The simulation model of the pelton jet turbine block is shown in Fig. 2. In this figure, a complete design of the pico hydro generator is presented by simulink blocks characterizing the mechanical and electrical parts of the system. These blocks are turbine, alternator, battery, inverter system. The produced rotational speed by hydro

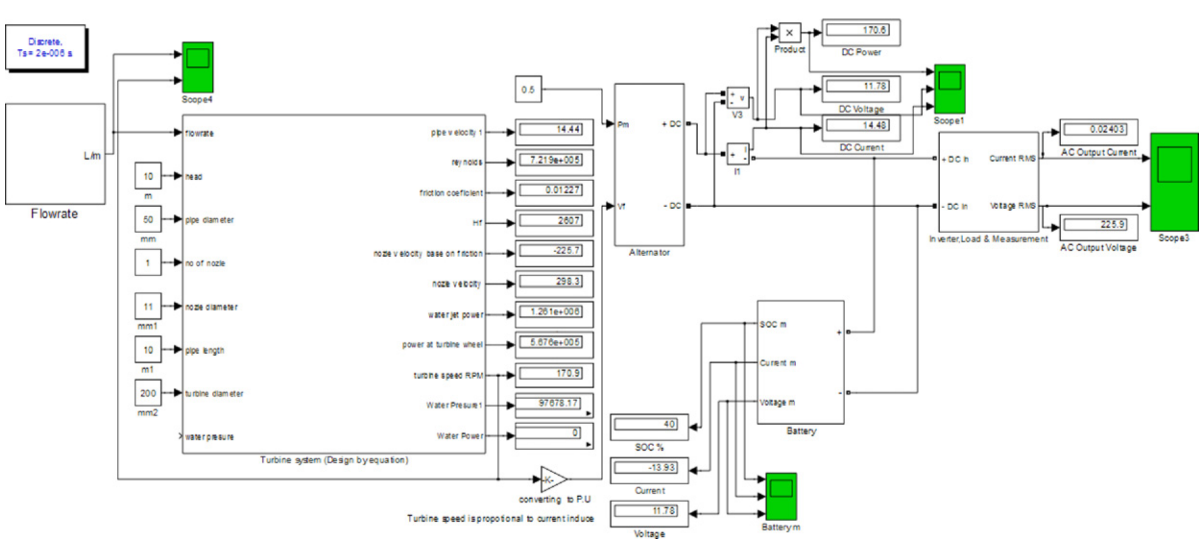


Fig. 2. Simulating block of pico hydro generator with charging unit.

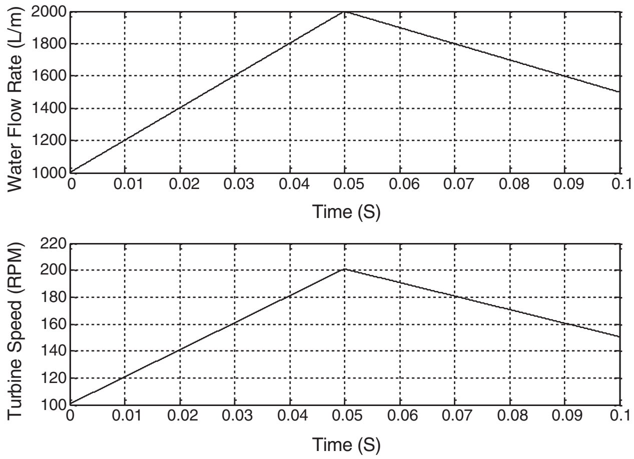


Fig. 3. Water flow and turbine speed of a pelton wheel turbine.

turbine generates electricity and the generator speed is proportional with the field voltage. The more speed of the rotor, the more current induce in the alternator stator at the constant field voltage of the alternator rotor. The generator terminal voltage, speed and power angle are teased by a measurement module. The terminal voltage is taken as the input of self-excitation system, and the outputs of excitation system are the DC excitation current of hydro generator.

Fig. 3 shows the water flow rate and the speed of the pelton wheel turbine. As seen from the graph of water flow rate, the water flow is simulated from intake pipe that is controlled by a valve. At the initial time ($t = 0$ s), the valve is set to be open for 1000 L/m. The initial speed of pelton wheel turbine for 1000 L/m is about 102 rpm for the water flow rate. The valve is continue to be open with maximum flow rate at 2000 L/m when $t = 0.05$ s and the pelton turbine speed is reaching to the maximum speed (202 rpm). Starting at $t = 0.05$ s, the valve is going to close in order to reduce the water flow rate until 1500 L/m at $t = 0.1$ s. The speed of turbine also will be reduced in the range of 152–202 rpm at $t = 0.1$ s. As seen from Fig. 3, the turbine speed is depending on the water flow rate. When there is an increasing in water flow rate, the turbine speed also increased.

To simplify the simulation of synchronous generator, the nominal speed of the generator had been previously set = 1 p.u. During this simulation, the field voltage can be varied and thus, it is proportional to the turbine speed. In real application, if the field voltage of generator is constant, the speed of the rotor will have an effect on the induced stator current. But if the field voltage is varying the rotor speed also varied as seen in Fig. 4. According to this figure, at

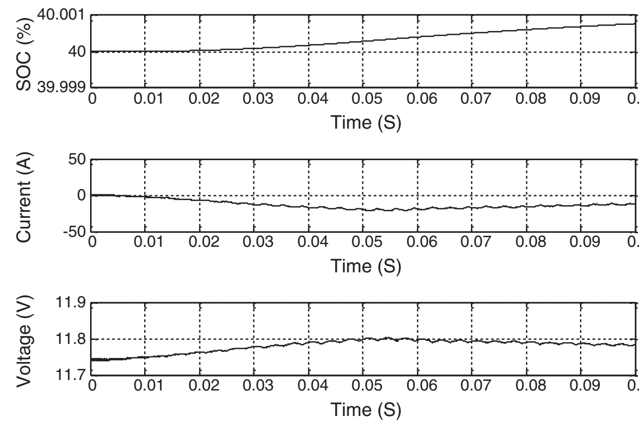


Fig. 5. Measurement values of battery.

$t = 0$ s until $t = 0.035$, the speed of rotor is high. Then, the rotor speed decreased when the field voltage increased. This indicates that the rotor dealt with a high torque produced by the electromagnetic field of the rotor.

Fig. 5 shows the voltage over the battery terminal. The initial voltage is 11.74 V then it was increased with time due to the change in power input at the alternator. From this figure, it is seen that the battery is in charging mode. Considering the state of charge (SOC) graph, the voltage can be raised up to a full charging voltage taking into account that each battery has its own specified charging capacity. The negative sign of current that can be appeared is due to the current flow from the alternator into the battery. The current is timely changed as the speed of turbine is changed. If the turbine speed is increased, the electromagnetic field also will be increased in the air gap between the rotor and stator, consequently, the induce current will be increased.

Fig. 6 shows the DC current output from the alternator after rectification. The current is inversely proportional to the battery current because the current is an output from alternator, while the battery is absorbing the alternator current. The induced current in the alternator is depending on the field voltage that applied to the rotor. If the field voltage is increased, the induced current also will be increased with change in time. Referring to Fig. 5, the DC voltage across the alternator output terminal is similar to the voltage output across battery terminal which means that the alternator and battery are in parallel condition. When the battery voltage is timely rising, the voltage across the alternator will be increased. Hence, the voltage or current increase will cause increase the output power. This is due to the fact that the output power from the alternator is the production of the voltage and current.

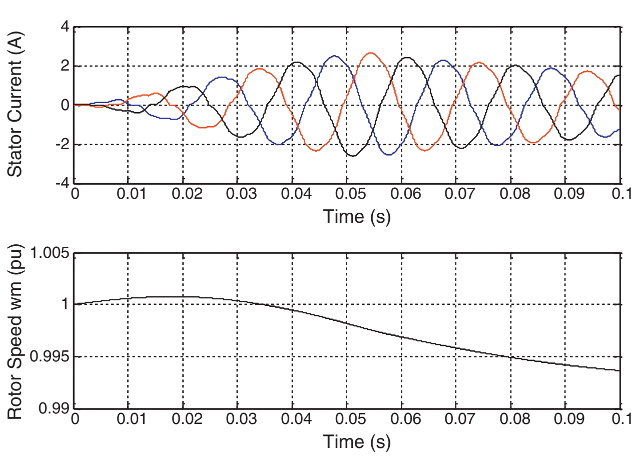


Fig. 4. The stator current and rotor speed of alternator.

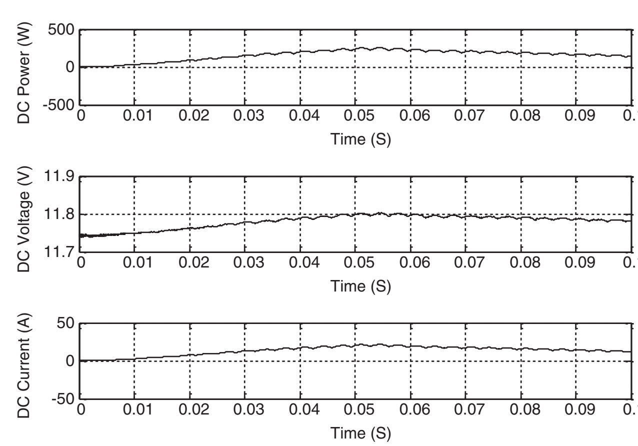


Fig. 6. The DC Current and voltage of converter.

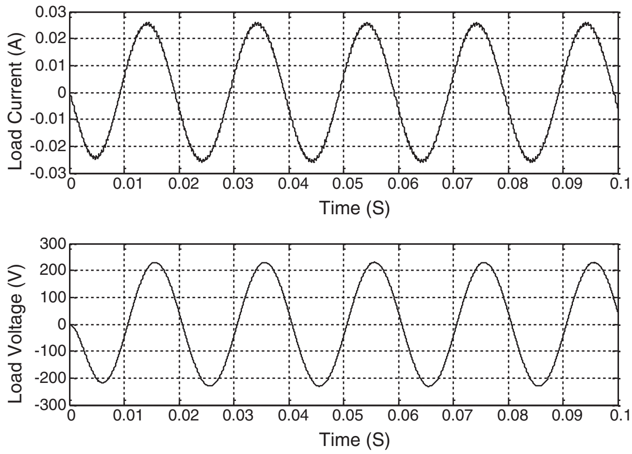


Fig. 7. Load voltage and current (output).

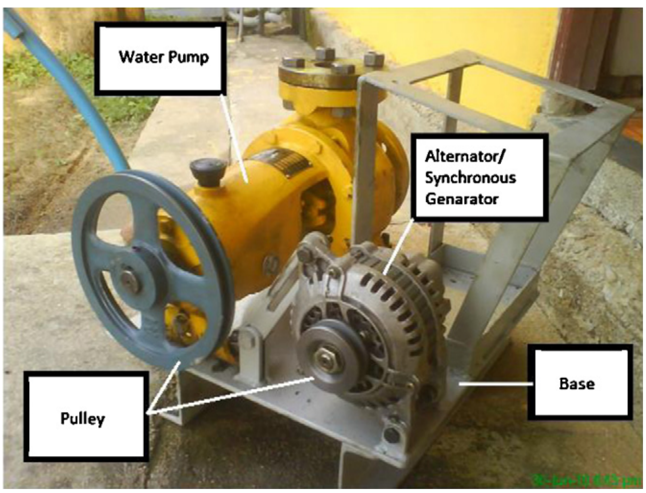


Fig. 8. Pico hydro compartment.

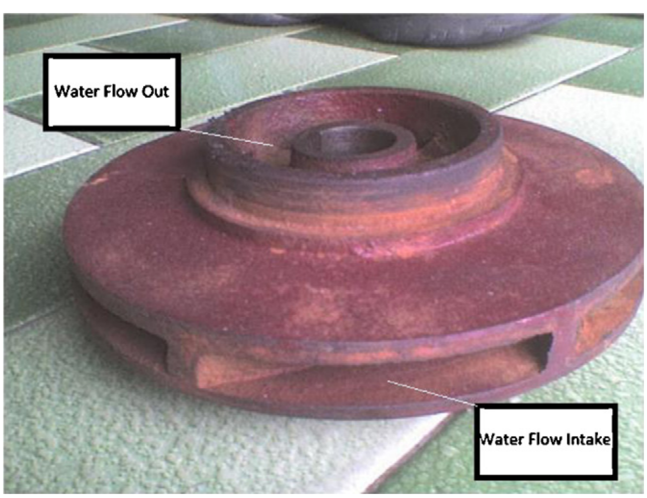


Fig. 9. Internal impeller.



Fig. 10. Pelton turbine.



Fig. 11. Pico hydro generation system in testing application.

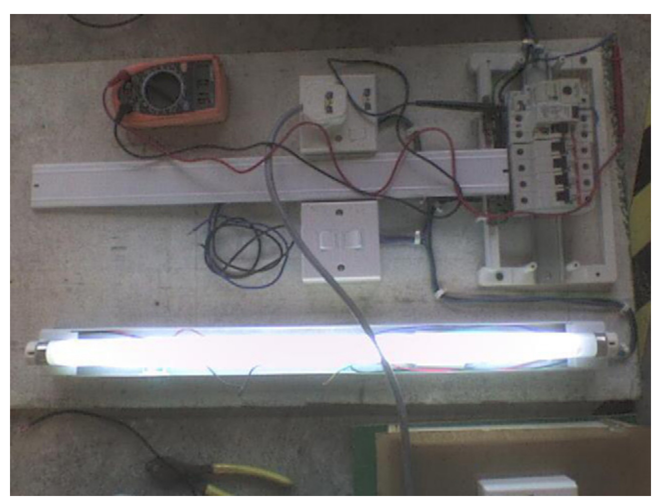


Fig. 12. Connected load into pico hydro generator.

Finally, the sinusoidal voltage and current output from the inverter are depicted in Fig. 7. As seen from this figure, the current value is very small since no load was applied and the appeared current is the value of no load loss occurred in the inverter and converter connections.

5. Implementation of pico hydro generation in UMP

The water flow rate of the fire hose at UMP was used to test the pico hydro generator. According to the building construction standard, this pressure is 14 bar and 0.23 m^3, the achieved power is



Fig. 13. Inverter output voltage and load current.



Fig. 14. Speed of rotor without and with field voltage applied to the rotor.



Fig. 15. Alternator DC voltage and current.

322 kW. Fig. 8 shows the compartment used to build a pico hydro generator. Here, the water pump is functioning as a turbine after the internal impeller of the water pump was modified into a pelton wheel as seen in Figs. 9 and 10 respectively. This modification was made in order to convert the kinetic energy from water flow into electrical energy produced by the Alternator. Referring to Fig. 9, the impeller of water pump cannot be use as a turbine because the construction of water flow out is bigger than the water intake. Moreover, the impeller is not running when the water pressure is low. Therefore, the impeller was modified into a pelton so that the water jet is getting enough water pressure to spin the turbine as fast as possible.

A complete pico hydro generation system in testing application is shown in Fig. 11. The generator is charging the battery and the battery is supplying the loads through an inverter. The lead acid battery (12 V 60 A H) is used to store the DC power. A 1 kW inverter is operating to convert DC supply from 12 V into 220 V AC 50 Hz. The alternator is a synchronous generator of Proton Iswara Car 1.5 L (14 V 75 A). A DC supply from lead acid battery is connected to the rotor of generator in order to induce a current at the stator. The

internal rectification is converting from AC to DC and the voltage is maintained in the range of 12–13 V to charge the battery. A panel of volt and ampere meters is attached to measure the RMS output voltage from inverter and the load current respectively.

Fig. 12 illustrates the connection of load supplied by pico hydro generator. The voltage output from inverter and the load current are seen in Fig. 13. Fig. 14 shows the speeds (rpm) of the rotor taken at the pulley of the alternator without and with field voltage applied to a rotor. As seen from the measured values in Fig. 14, the results are the same with the simulation, when the rotor is running without field voltage the speed is more than the running with field voltage which means that the rotor is dealing with a high torque when there is a voltage supply at the rotor. The output DC voltage and current from the alternator are shown in Fig. 15 and this current depends on the speed and field voltage of the rotor. The negative sign means that the current is flowing into the battery for charging. A charge controller for battery protection is used to cut off the supply when the battery at maximum charging level. A power drop recovery sensor can be applied to detect the voltage drop at the AC output terminal. This correction can be made at the generation side by regulating (increasing) the field voltage of generator in order to maintain the AC output voltage.

6. Conclusion

In this work, the potential of small hydropower development is given as an example of a real pico hydro generator which is prepared for installation at the main tank location of UMP campus in Pekan. The presented design and running procedures of a pico hydro generator with a simple modeling and simulation using Matlab can be implemented in any location where the flow water of the reservoir is reachable. The research study has shown that the stand-alone pico hydro system can generate electricity. This system is a financial attractive and environmentally friendly solution at a particularly attractive price. In addition, pico hydro generators will contribute remarkably to reduce the energy demand problems of domestic and commercial consumers. Finally, pico hydro systems are usually the lowest cost option for off-grid rural electrification where there is a suitable site.

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